Gear Cutting

Introduction

Gears transmit power or motion mechanically between parallel, intersecting, or non-intersecting shafts. Although usually hidden from sight, gears are one of the most important mechanical elements in our civilization. Gears operate at a very high speed ranges under a wide variety of conditions. Millions are produced each year in sizes from a few millimeters up to more than 10 m in diameter. Often the requirements that must be, and are routinely, met in their manufacture are amazingly precise. Consequently, the machines and processes that have been developed for producing gears are among the most ingenious we have. To understand the functional requirements of these machines and processes, it is helpful to consider the basic theory of g. and their operation.

Gear Theory and Terminology

Basically, gears are modifications of wheels, with gear teeth added to prevent slipping and to assure that their relative motions are constant. However, it should be noted that the relative surface velocities of the wheels (and shafts) are determined by the diameters of the wheels.

Although wooden teeth were attached to disks to make gears in ancient times, the teeth of modern gears are produced by machining or forming teeth on the outer portion of the wheel. The pitch circle (Figure 1 and Figure 2) corresponds to the diameter of the wheel. Thus the angular velocity of a gear is determined by the diameter of this imaginary pitch circle. All design calculations relating to gear performance are based on the pitch-circle diameter or, more simply, the pitch diameter (PD).

For two gears to operate properly, their pitch circles must be tangential to each other. The point at which the two pitch circles are tangent, at which they intersect the centerline connecting their centers of rotation, is called the pitch point. The common normal at the point of contact of mating teeth must pass through the pitch point. This condition is illustrated in Figure 2.

To provide uniform pressure and motion and to minimize friction and wear, gears are designed to have rolling motion between mating teeth rather than sliding motion. To achieve this condition, most gears utilize a tooth form that is based on an involute curve. This is the curve that is generated by a point on a straight line when the line rolls around a base circle. A somewhat simpler method of developing an involute curve is that shown in Figure 3, by unwinding a tautly held string from a base circle: point A generates involute curve.

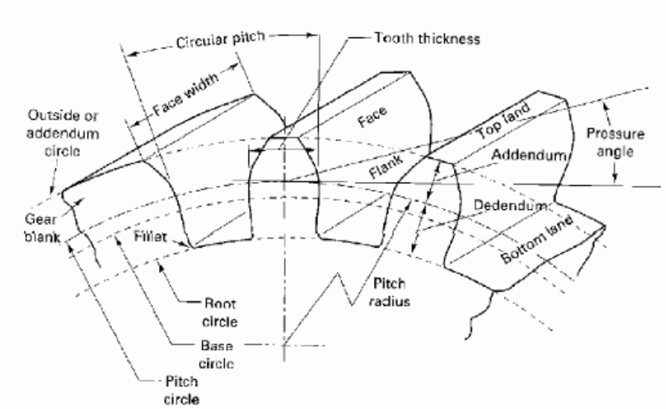


Fig. 1: Gear tooth nomenclature

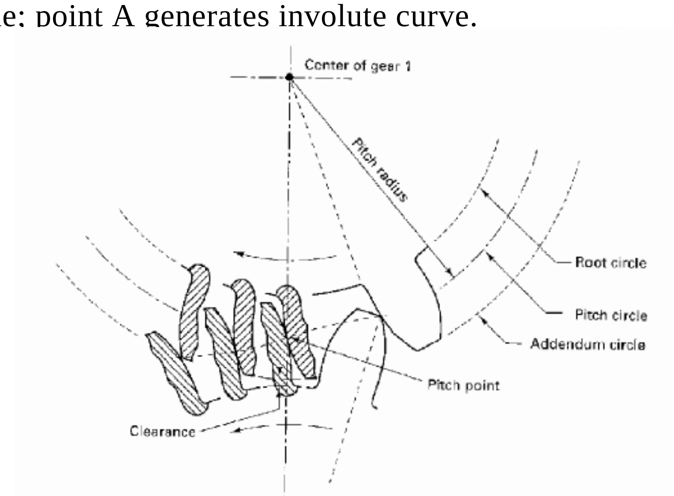


Fig. 2: Tangent pitch circles between two gears produces a pitch pointGear tooth nomenclature

There are three other reasons for using the involute form for gear teeth. First, a tooth form provides the desired pure rolling action. Second, even if a pair of involute gears is operated with the distance between the centers slightly too large or too small, common normal at the point of contact between mating teeth will always pass through pitch point. Obviously, the theoretical pitch circles in such cases will be increased or creased slightly. Third, the line of action, or path of contact, that is, the locus of the point of contact of mating teeth, is a straight line that passes through the pitch point and is tangent to the base circles of the two gears.

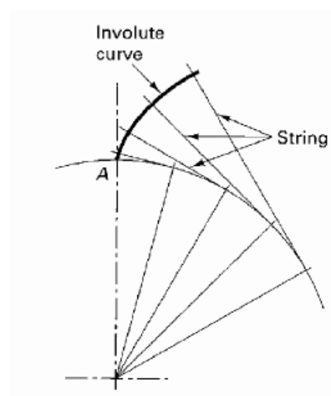


Fig. 3: Method of generating an involute curve by unwinding a string from a cylinder

Cutting an involute shape in gear blanks can be done by simple form cutting (i.e., milling the shape into the workpiece) or by generating. Generating involves relative motion between the workpiece and the cutting tool. True involute tooth form can be produced by a cutting tool that has straight-sided teeth. This permits a very accurate involute profile to be obtained

through the use of a simple and easily made cutting tool. The straight-sided teeth are given a rolling motion relative to the workpiece to create the curved gear-tooth face.

The basic size of gear teeth may be expressed in two ways. The common practice, especially in the United States and England, is to express the dimensions as a function of the diametral pitch (DP). DP is the number of teeth (N) per unit of pitch diameter (PD thus DP = N/PD. Dimensionally, DP involves inches in the English system and millimeters in the SI system, and it is a measure of tooth size. Metric gears use the m system (M), defined as the pitch diameter divided by the number of teeth, or M = PD/N. It thus is the reciprocal of diametrical pitch and is expressed in millimeters. Any two gears having the same diametral pitch or module will mesh properly if they are mounted so as have the correct distances and relationship.

The important tooth elements can be specified in terms of the diametral pitch or the module and are as follows:

1. Addendum: the radial distance from the pitch circle to the outside diameter.

   Addendum = 1/DP mm
2. Dedendum: the radial distance from the pitch circle to the root circle. It is equal to the addendum plus the clearance, which is provided to prevent the outer corner of a tooth from touching against the bottom of the tooth space.
3. Circular pitch: the distance between corresponding points of adjacent teeth, measured along the pitch circle. It is numerically equal to π/diametrical pitch.
4. Tooth thickness: the thickness of a tooth, measured along the pitch circle. When tooth thickness and the corresponding tooth space are equal, no backlash exists in a pair of mating gears.
5. Face width: the length of the gear teeth in an axial plane.
6. Tooth face: the mating surface between the pitch circle and the addendum circle.
7. Tooth flank: the mating surface between the pitch circle and the root circle.
8. Pressure angle: the angle between a tangent to the tooth profile and a line perpendicular to the pitch surface.

Four shapes of involute gear teeth are used:

1. 14½ ° pressure angle, full depth (used most frequently)

2. 14½ ° pressure angle, composite (seldom used)
3. 20° pressure angle, full depth (seldom used)
4. 20° pressure angle, stub tooth (second most common)

In the 14½° full-depth system, the tooth profile outside the base circle is an involute curve. Inward from the base circle the profile is a straight radial line that is joined with the bottom land by a small fillet. With this system, the teeth of the basic rack have straight sides.

The 14½° composite system and the 20° full-depth system provide somewhat stronger teeth. However, with the 20° full-depth system, considerable undercutting occurs in the dedendum area; therefore, stub teeth often are used. The addendum is shortened by 20%, thus permitting the dedendum to be shortened a similar amount. This results in very strong teeth without undercutting.

Physical Requirements of Gears

A consideration of gear theory leads to five requirements that must be met in order for gears to operate satisfactorily:

1. The actual tooth profile must be the same as the theoretical profile.
2. Tooth spacing must be uniform and correct.
3. The actual and theoretical pitch circles must be coincident and be concentric with the axis of rotation of the gear.
4. The face and flank surfaces must be smooth and sufficiently hard to resist wear and prevent noisy operation.
5. Adequate shafts and bearings must be provided so that desired center-to-center distances are retained under operational loads.

The first four of these requirements are determined by the material selection and manufacturing process. The various methods of manufacture that are used represent attempts to meet these requirements to varying degrees with minimum cost, and their effectiveness must be measured in terms of the extent to which the resulting gears embody these requirements. Before looking at the ways to manufacture gears, let's look at some examples

of gears.

Gear Types

Spur Gears: The more common types of gears are shown in Figure 4. Spur gears have straight teeth and are used to connect parallel shafts. They are the most easily made and the cheapest of all types.

Fig. 4: Types of gears: a) spur gear and rack; b) worm and worm gear; c)spiral bevel gear; d)helical gears; e) crown gear; f) straight bevel gears; g) zerol bevel gear; h) hypoid bevel gear; k) continuous herringbone gears

Helical Gears: The teeth on helical gears lie along a helix, the angle of the helix being the angle between the helix and a pitch cylinder element parallel with the gear shaft. Helical gears can connect either parallel or nonparallel nonintersecting shafts. Such gears are stronger and quieter than spur gears because the contact between mating teeth increases more gradually and more teeth are in contact at a given time. Although they usually are slightly more expensive to make than spur gears, they can be manufactured in several ways and are produced in large numbers.

Helical gears have one disadvantage. When they are in use, a side thrust is created that must be absorbed in the bearings. Herringbone gears neutralize this side thrust by having, in effect, two helical-gear halves, one having a right-hand and the other a left-hand helix. The continuous herringbone type is rather difficult to machine but is very strong. A modified herringbone type is made by machining a groove, or gap, around the gear blank where the two sets of teeth would come together. This provides a run-out space for the cutting tool in making each set of teeth.

Rack: A rack is a gear with infinite radius, having teeth that lie on a straight line on a plane. The teeth may be normal to the axis of the rack or helical so as to mate with spur or helical gears, respectively.

Worm gear: A worm is similar to a screw. It may have one or more threads, the multiple-thread type being very common. Worms usually are used in conjunction with a worm gear. High gear ratios are easily obtainable with this combination. The axes of the worm and worm gear are nonintersecting and usually are at right angles. If the worm has a small helix angle, it cannot be driven by the mating worm gear. This principle frequently is employed to obtain nonreversible drives. Worm gears usually are made with the top land concave to permit greater area of contact between the worm and the gear. A similar effect can be achieved by using a conical worm, in which the helical teeth are cut on a double-conical blank, thus producing a worm that has an hourglass shape.

Bevel Gears: teeth on a cone, are used to transmit motion between intersecting shafts. The teeth are cut on the surface of a truncated cone. Several types of bevel gears are made, the types varying as to whether the teeth are straight or curved and whether the axes of the mating gears intersect. On straight-tooth bevel gears the teeth are straight, and if extended all would pass through a common apex. Spiral-tooth bevel gears have teeth that are segments of

spirals. Like helical gears, this design provides tooth overlap so that more teeth are engaged at a given time and the engagement is progressive. Hypoid bevel gears also have a curved-tooth shape but are designed to operate with nonintersecting axes. Rear-drive automobiles used hypoid gears in the rear axle so that the drive shaft axis can be below the axis of the axle and thus permit a lower floor height. Zerol bevel gears have teeth that are circular arcs, providing somewhat stronger teeth than can be obtained in a comparable straight-tooth gear. They are not used extensively. When a pair of bevel gears are the same size and have their shafts at right angles, they are termed miter gears.

A crown gear is a special form of bevel gear having a 180° cone apex angle. In effect, it is a disk with the teeth on the side of the disk. It also may be thought of as a rack that has been bent into a circle so that its teeth lie in a plane. The teeth may be straight or curved. On straight-tooth crown gears the teeth are radial. Crown gears seldom are used, but they have the important quality that they will mesh properly with a bevel gear of any cone angle, provided that the bevel gear has the same tooth form and diametral pitch. This important principle is incorporated in the design and operation of two very important types of gear-generating machines that will be discussed later. Most gears are of the external type, the teeth forming the outer periphery of the gear. Internal gears have the teeth on the inside of a solid ring, pointing toward the center of the gear.

Gear Manufacturing

Whether produced in large or small quantities, in cells, or job shop batches, the sequence of processes for gear manufacturing requires four sets of operations:

1. Blanking
2. Gear cutting
3. Heat treatment
4. Grinding

Blanking refers to the initial forming or machining operations that produce a semi-finished part ready for gear cutting, starting from a piece of raw material. Good-quality blanks are essential in precision gear manufacturing. Hobbing, shaping, and shaving

machines are the most frequently used machines for gear cutting, producing gears for automotive, truck, agricultural, and construction equipment. Other processes used in industrial gear production include broaching, rolling, grinding, milling, and shiving. The process selected depends on finding a cost-effective application based on quality specification, production volumes, and economic conditions.

The gear cutting or machining operations can be divided into operations executed prior to heat treatment, when the material is still soft and easily machinable and after heat treatment, performed on parts that have acquired high hardness and strength.

Heat treatment gives the material the strength and durability to withstand high loads and wear but results in a reduction in dimensional and geometrical accuracy. The metallurgical transformations that occur during hardening, quenching, and tempering cause a general quality deterioration in the gears. Therefore, precision grinding operations are used on external and internal bearing diameters, critical length dimensions, and fine surface finishes after heat treatment. Cylindrical grinders, angle-head grinders, internal grinders, and surface grinders are commonly used.

Gears are made in very large numbers by cold-roll forming, and in addition, significant quantities are made by extrusion, by blanking, by casting, and some by powder metallurgy and by a forging process. However, it is only by machining that all types of gears can be made in all sizes, and although roll-formed gears can be made with accuracy sufficient for most applications, even for automobile transmissions, machining still is unsurpassed for gears that must have very high accuracy. Also, roll forming can be used only on ductile metals.

Gear Cutting Methods

Toothed-gears are indispensable elements in mechanical transmission of power, and their accurate production necessitated the development of ingenious tools and processes. Gears may be manufactured by casting, stamping, machining or by powder metallurgical processes. Out of all such processes, the most common and accurate method of production of gears is by machining. The different methods of production of gears by machining operations are described below.

1. Formed cutter method:

   a. By a formed disc cutter in a milling machine.
   b. By a formed end mill in a milling machine.
   c. By a formed single point tool in a shaping or planing machine.
   d. By a formed cutter in a "shear speed" gear shaper.
   e. By a formed cutter in a broaching machine.
2. Template method in a gear cutting machine
3. Generating method :
   a. By a rack tooth cutter in a gear cutting machine.
   b. By a pinion cuter in a gear cutting machine.
   c. By a hob cutter in a gear cutting machine.
   d. By a bevel gear generator.

Formed Cutter Method

The formed cutter method of production of gear uses a single point cutting tool or a milling cutter having the same form of cutting edge as the space between the teeth being cut. The form cutting method is only used where a very small number of gears are to be manufactured and where too much of accuracy is not demanded. The method uses simple and cheap tools in conventional machines and the set up required is also simple. The formed method possesses certain inherent disadvantages. These are described below.

1. The gear tooth accuracy is very poor.
2. The production capacity is very low due to wastage in machining time for indexing withdrawing, and advancing the cutter or the work after machining each tooth space.

Gear Cutting By Formed Disc Cutter

The method of gear cutting by a formed disc cutter involves the mounting of a gear blank at the end of a dividing head spindle fitted on the table of a horizontal, column and knee type milling machine and then feeding the work past a rotating, formed, peripheral type of cutter mounted on the horizontal arbor of the machine. The plane of

rotation of the cutter is radial with respect to the blank. After one tooth space is formed, the next surface of the gear blank is brought under the cutter by rotating the dividing head spindle by a predetermined amount by indexing. The tooth profile of the formed cutter should correspond to the tooth space of the gear that again depends upon the module of the gear. Theoretically, there should be a different shaped cutter for each number of teeth of gears of the same module, as the tooth profile of the involute gears changes with the number of teeth on the gear. In practice, a set of 8 cutters are used to cut all gears having teeth ranging from 12 to a rack. This is a compromise with the theoretical value. For this reason, the gear tooth profile produced by a formed disc cutter is not perfectly accurate. The set of cutters used for cutting different numbers of gear teeth is shown in the following table. A spur, helical or a bevel gear can be cut in a milling machine by using a formed disc cutter.

Cutter No.	1	2	3	4	5	6	7	8
No. of teeth cut	135-rack	55-134	35-54	26-34	21-25	17-20	14-16	12-13

Fundamental of spur Geer Milling by a Formed Disc Cutter

The cutting of spur gear in a milling machine involves the following procedure:

1. To determine the important dimensions and proportions of the gear tooth element.
2. To control the spacing of the gear teeth accurately on the periphery of the gear blank.
3. To select the correct number of cutter for the required number of teeth on the gear.
4. To determine the proper speed of the cutter, feed of the table, and the depth of cut.
5. To set the cutter and the work to perform the actual operation.

Spur Gear Proportions

The first step in machining a spur gear is to determine the important gear tooth dimensions. The tip or outside diameter should be known to prepare the gear blank diameter. The tooth depth is necessary to calculate for setting the depth of cut of the cutter. From the module and the

number of teeth on the gear, the pitch circle diameter can be calculated, and from the chordal thickness the size of the gear tooth can be checked.

Form cutting or form milling is illustrated in Figure 5. The cutter has the same form as the space between adjacent teeth. Usually, a multiple-tooth form cutter (Figure 6) is used, as shown in Figure 5. The tool is fed radially toward the center of the gear blank to the desired tooth depth, then across the tooth face to obtain the required tooth width. When one tooth space has been completed, the tool is withdrawn, the gear blank is indexed using a dividing head, and the next tooth space is cut. Basically, form cutting is a simple and flexible method of machining gears. The equipment and cutters required are relatively simple, and standard machine tools (milling machines) often are used. However, in most cases the procedure is quite slow, and considerable care is required on the part of the operator; therefore, it usually is employed where only one or a few gears are to be made. In machining gears by the form-cutting process, the form cutter is mounted on the machine spindle, and the gear blank is mounted on a mandrel held between the centers of some type of indexing device. Figure 7 shows the arrangement that is employed when, as is often the case, the work is done on a universal milling machine; the cutter is mounted on an arbor, and a dividing head is used to index the gear blank. When a helical gear is to be cut, as in the case shown, the table must be set at an angle equal to the helix angle, and the dividing head is geared to the longitudinal feed screw of the table so that the gear blank will rotate as it moves longitudinally.

Standard cutters usually are employed in form-cutting gears. In the United States, these come in eight sizes for each diametral pitch and will cut gears having the number of teeth indicated earlier. A single cutter will not produce a theoretically perfect tooth profile for all sizes of gears in the range for which it is intended. However, the change in tooth profile over the range covered by each cutter is very slight, and most of the time, satisfactory results can be achieved. Cutters are available for all common diametral pitches and 14½ and 20° pressure angles.

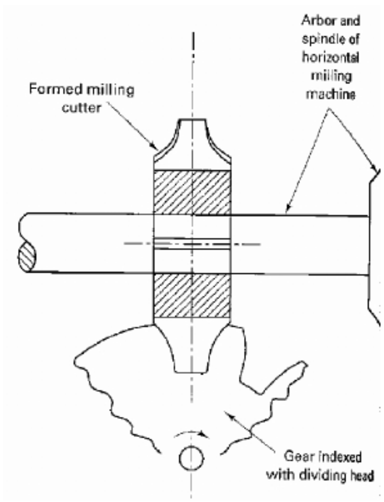


Fig. 5: Basic method of machining a gear by form milling.

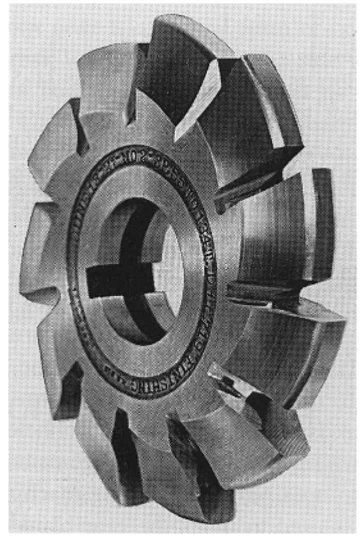


Fig. 6: Form milling cutter.

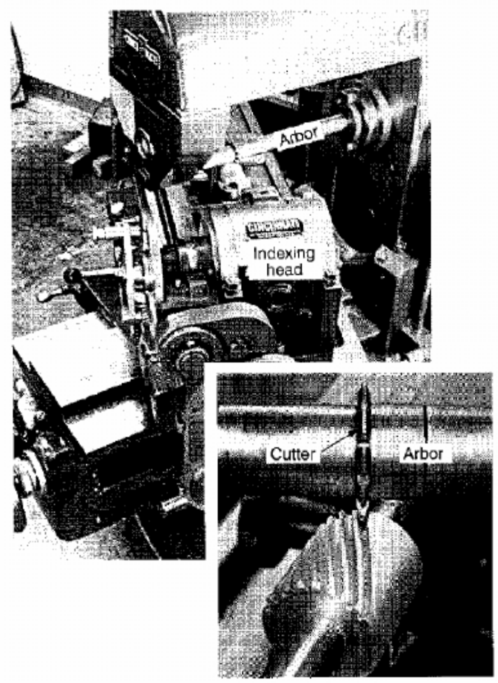


Fig. 7: Form cutting a helical gear on a universal milling machine using an indexing head.

Straight-tooth bevel gears can be form cut on a milling machine, but this is seldom done. Because the tooth profile in bevel gears varies from one end of the tooth to the other, after one cut is taken to form the correct tooth profile at the smaller end, the relationship between the cutter and the blank must be altered. Shaving cuts then are taken on the side of each tooth to form the correct profile throughout the entire tooth length. Although the form cutting of gears on a milling machine is a flexible process and is suitable for gears that are not to be operated at high speeds or that need not operate with extreme quietness, the process is slow and requires skilled labor. Semi-automatic machines are available for making gears by the form-cutting process.

Indexing and Dividing Heads

The indexing is the operation of dividing the periphery of a piece of work into any number of equal parts. In cutting spur gear, equal spacing of teeth on the gear blank is performed by indexing. The indexing operation can also be adapted for producing hexagonal and square-headed bolts, cutting splines on shafts, fluting drills, taps and reamers and many other jobs all requiring the periphery of the workpiece to be divided equally and accurately. Indexing is accomplished by using a special attachment known as dividing head or index head. The dividing heads are of three types:

1. Plain or simple dividing head,
2. Universal dividing head and
3. Optical dividing head.

Plain or simple dividing head: The plain dividing head comprises a cylindrical spindle housed in a frame, and a base bolted to the machine table. The index crank is connected to the tail-end of the spindle directly, and the crank and the spindle rotate as one unit. The index plate is mounted on the headstock frame. The spindle may be rotated through the desired angle and then clamped by inserting the clamping lever pin into any one of the equally spaced holes or slots cut on the periphery of the index plate. The work is mounted at the nose end of the spindle by a chuck or may be supported between the two centres. The live centre is fitted at the nose of the spindle and the dead centre is held by the tailstock. The tailstock is a separate assembly which is bolted to the machine table after aligning its spindle axis with the dividing head spindle. This type of dividing head is used for handling large number of workpieces, which require a very small number of divisions on the periphery

Universal dividing head: The universal dividing head shown in Figure 8 is the most common type of indexing arrangement used in workshops. As the name implies, this type of index head can be used to execute all forms of indexing. A universal dividing head is used for the following purposes:

1. For setting the work in vertical, horizontal or in inclined positions, relative to the table surface.

2. For turning the workpiece periodically through a given angle to impart indexing movement.
3. For imparting a continuous rotary motion to the workpiece for milling; helical grooves.

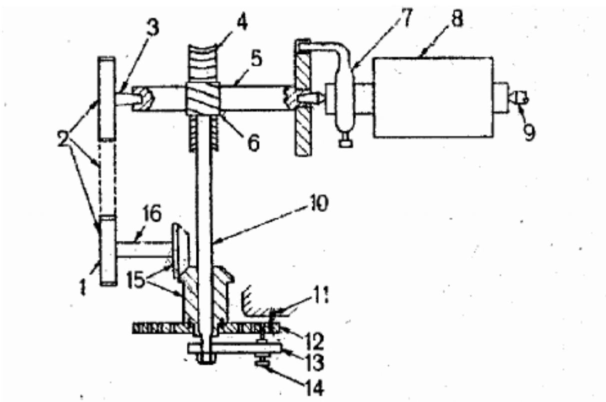
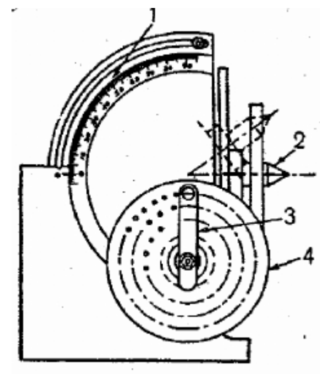


Fig. 8 Working mechanism of a universal dividing head
1, 2. *Change gears*, 3. *Spindle stud*, 4. *Worm gear*, 5. *Spindle*, 6. *Worm*, 7. *Carrier*, 8. *Work*, 9. *Dead centre*, 10. *Worm shaft*, 11. *Lockpin*, 12. *Indexplate*, 13. *Index-crank*, 14. *Spring loaded pin*, 15. *Mitre gears*, 16. *Driven shaft*.



Universal dividing head
1. *Swivelling block*, 2. *Live centre*, 3. *Index crank*, 4. *Index plate*

The important parts of a universal dividing head are the worm and worm gear, index plate, sector arm, change gears and the spindle. The working mechanism of a universal indexing head is shown in Figure 8. The main spindle (5) housed on two accurate bearings carries a worm gear (4), which is keyed on it. The worm (6) which meshes with the worm gear (4) is mounted on a shaft (10) at the other end to which a crank (13) is fitted. The worm gear (4) has 40 teeth and the worm (6) is single threaded. Thus 40 turns of the crank (13) will rotate the spindle (5) through one complete revolution or one turn of the crank (13) will cause the spindle (5) to be rotated by 1/40 of a revolution. An index plate (12) is used. An index plate is a circular disc having a different number of equally spaced holes arranged in concentric circles. The index plate (12) is screwed on a sleeve which is loosely mounted on the worm shaft (10). Normally, the index plate (12) remains stationary by a lock pin (11) connected with the frame. A spring loaded pin (14) fixed to the crank (13) fits into the holes in the index plate (12). If the pin (14) is moved froth one hole to the next hole in a 18 hole circle of the index plate, the spindle (5) will revolve $1/40 \times 1/18 = 1/720$ of a turn. The sector arms are used to eliminate the necessity of counting holes on the index plate each time the index crank is moved. The dividing head spindle (5) is provided with a taper hole at the nose for accommodating a live centre. The nose is threaded on the outside for mounting a chuck or a faceplate. The work (8) may be supported between the

two centres (9) or on a chuck.

The spindle (5) is supported on a swiveling block which enables the spindle to be tilted through any angle 5° below horizontal to 10° beyond vertical, and then clamped at that position. The angular setting of the dividing head is affected by using a graduated scale fitted to the body of the dividing head. This is illustrated in Figure 8.

The dividing head spindle may be connected with the table feed screw through a train of gearing to impart a continuous rotary motion to the workpiece for helical milling.

Optical dividing head: The optical dividing heads are used for precise angular indexing during machining, and for checking the accuracy of various angular surfaces. The mechanism comprises a worm gear which is keyed to the spindle and may be rotated by a worm. A circular glass scale graduated in 1° division is rigidly mounted on the worm wheel. Any movement of the spindle affected by rotating the worm is read off by means of a microscope fitted on the dividing head body. The reading on the circular glass scale is projected through prisms on the screen of the microscope's eyepiece. The eyepiece has a scale having 60 divisions and each division is equivalent to 1 movement of the circular scale. Thus with this arrangement, a precise indexing movement can be made.

Indexing Methods

There are several different methods for indexing. The choice of any one method depends upon the number of divisions required and the type of dividing head used. The following are the different methods of indexing:

1. Direct or rapid indexing
2. Plain or simple indexing
3. Compound indexing
4. Differential indexing
5. Angular indexing

Direct Indexing: Direct indexing, often called rapid indexing, is used when a large number of identical pieces are indexed by very small divisions. The operation may be performed in both.

plain and universal dividing head. When using a universal head, the worm and worm wheel are first disengaged. This is done in a manner similar to that used in the back gear of a lathe by turning a handle which operates an eccentric bushing. The required number of divisions on the work is obtained by means of the rapid index plate generally fitted to the front end of the spindle nose. The plate has 24 equally spaced holes, into any one of which a spring loaded pin is pushed to lock the spindle with the frame. While indexing, the pin is first taken out and then the spindle is rotated by hand, and after the required position is reached it is locked again by the pin. When the plate is turned through the required part of a revolution, the dividing head spindle and the work are also turned through the same part of the revolution. With a rapid index plate having 24 holes it is possible to divide the work into equal divisions of a, 3, 4, 6, 8 and 24 parts which are all factors of 24.

Rule for direct indexing: To find the index movement, divide the total number of holes in the direct index plate by the number of divisions required on the work. In this case, when the direct index plate has 24 holes, the formula for indexing is given below:

No. of holes to be moved = 24/N, where N = number of divisions required.

Example 1: find out the index movement required to mill a hexagonal bolt by direct indexing. The rapid index plate has 24 holes.

No. of holes to be moved = 24/6 = 4

After machining one side of the bolt, the index plate will have to be moved by 4 holes for 5 number of times to machine the remaining faces of the bolt.

Simple Indexing: The simple indexing, sometimes called plain indexing, is more accurate and suitable for numbers beyond the range of rapid indexing. Here, the dividing heat spindle is moved by turning the index crank (13). As the shaft (10), carrying the crank has a single threaded worm (6), which meshes with the worm gear (4) having 40 teeth, 40 turns of the crank (13) are necessary to rotate the index head spindle (5) through one revolution. In other words, one complete turn of the index crank (13) will cause the worm wheel (4) to make 1/40 of a revolution. To facilitate indexing to fractions of a turn, index plates are used to cover

practically all numbers.

Index plates with circles of holes patented by the Brown and Sharpe manufacturing company are as follows :

Plate No. 1	15	16	17	18	19	20
Plate No. 2	21	23	27	29	31	33
Plate No. 3	37	39	41	43	47	49

These plates have also been accepted as standard index plates by the Indian machine tool manufactures. With the three index plates supplied, simple indexing can by used for all divisions up to 50, even numbers up to 100, except 96, and many others.

Rule for simple indexing: To find the index crank movement, divide 40 by the number of divisions required on the work. The formula for index crank movement is given below:

Index crank movement =40/N, where N = number of divisions required.

If the index crank movement deduced from the previous formula is a whole number, the index crank should be rotated through a complete number of turns equal to the derived whole number. If the index crank movement deduced from the last equation is a whole number and a fraction, the numerator and the denominator of the fraction after simplifying are multiplied by a suitable common number which will make the denominator of the fraction equal to the number of holes in the index plate circle. The new numerator now stands for the number of holes to be moved by the index crank in the hole circle derived from the denominator in addition to the complete turns of the index crank.

Example 2: Set the dividing head to mill 30 teeth on a spur wheel blank.

Index crank movement = 40/30 = 1 1/3 = 1 7/21.

Thus for indexing, one complete turn and 7 holes in 21 hole circle of the index plate will have to be moved by the index crank.

Compound Indexing: The indexing method is called compound due to the two separate movements of the index crank in two different hole circles of one index plate to obtain a

crank movement not obtainable by plain indexing. The index plate is normally held stationary by a lock pin which engages with one of the hole circles of the index plate from the back. While indexing, first the crank pin is rotated through a required number of spaces in one of the hole circles of the index plate and then the crank pin is engaged with the plate. This first movement is performed similar to the plain indexing. The second index movement is now given by removing the rear lock pin and then rotating the plate together with the index crank forward or backward through the calculated number of spaces of another hole circle, and then the lock pin is engaged. The effective indexing movement will be the summation of the two movements. The method of finding the index crank movement being a complicated one is seldom used these days.

Rule for compound indexing: The rule for compound indexing is given by the formula:

$40/N = n_1/N_1 \pm n_2/N_2$,

where N = the number of divisions required.

N_1 = the hole circle used by the crank pin

N_2 = the hole circle used by the lock pin

n_l = the hole spaces moved by the crank pin in N_1 hole

n2 = the hole spaces moved by the plate and the crank pin in N_2 hole circle.

Procedure for determining the index circles:

Procedure I: The following procedure should be adapted for compound indexing a number which can be easily factorized.

1. Resolve into factors the number of divisions required.
2. Choose at random two hole circles.
3. Subtract the hole numbers of one circle from the other.
4. Factor the difference.
5. Place the factors of the divisions required and the factors of the difference above a horizontal line.
6. Next factor the number of turns of the crank required for one revolution of the spindle (4) and also factor the hole circles chosen.
7. Place these three new factors below the horizontal line.
8. Cancel the common factors above and below the line. If all the factors above the line

can be cancelled by those Placed below, then the two circles chosen can be used for indexing. If the factors above the line cannot be completely cancelled then two other hole circles should be chosen for trial cancellation.

9. The factors which will remain un-cancelled below the circle to be moved by the two indexing movements.

<u>Example 3</u>: Index 69 divisions by compound indexing. Using the aforementioned formula.

$40/69 = n_1/N_1 \pm n_2/N_2$

To determine the values of n_1, N_1, n_2 the above procedure is followed step by step.

1. 69=23×3
2. Index circles 23 and 33 are chosen
3. 33-23=10
4. 10=2×5
5. 69=23×3

   10=2×5
6. 40=2×2×5

   23=23×1

   33=3×11
7. & 8. $69=\cancel{23}\times\cancel{3}$

   $10=\cancel{2}\times\cancel{3}$

   $40=\cancel{2}\times2\times2\times\cancel{3}$

   $23=\cancel{23}\times1$

   $33=\cancel{3}\times11$

As all the numbers can be cancelled above the horizontal line, the hole circles 23 and 33 can be used for indexing. Thus $N_1 = 23$ and $N_2 = 33$

9. 2 x 2 x 11 = 44

44 is the number of hole spaces to be moved for indexing. The last formula can now be

resolved as: 40/69 = 44/23 – 44/33 = 1 21/23 – 1 11/33 = 21/23 – 11/33

Thus for indexing 69 divisions, the index crank should be, moved by 21 holes in 23 hole circle in forward direction: .and then the plate and the crank together is moved by 11 holes in 33 hole circle in the backward direction.

Procedure II: For compound indexing a number which cannot be factorised and. for many-other numbers, the actual index movement of the work is given several times grater than the actual spacing required, and finally the-required divisions are obtained or the work.

Differential Indexing: The indexing method is called differential because the required division is obtained by a .combination of two movements:

1. The movement of the index crank similar to the simple indexing.
2. The simultaneous movement of the index plate when the crank is turned.

The rotation or differential motion of the index plate may take place in the same direction as the crank or opposite to it as may be required. The result is that the actual movement of the crank at every indexing is automatically increased or decreased giving the required index movement of the spindle. For this reason, the differential indexing may be considered as an automatic method of performing compound indexing.

In Figure(8) while differential indexing, the lock pin (11) is disengaged with the index plate (12) which is screwed to a sleeve, a miter gear (15) is fastened to the other end of the sleeve. The index plate (12), the sleeve and the miter gear (15) are free to rotate on the worm shaft (12). The miter gear (15) meshes with another miter gear (15) on shaft (16). The tail end of the spindle (5) holds a stud (3). The change gears (2) may be mounted between the stud (3) and shaft (16). The gear on the spindle (5) is a driving gear and the gear on the shaft (16) is the driven gear. The Change gear train (2) may be simple or compound. Now with this gearing arrangement, as the index crank (13) is turned, rotating the spindle (5), the index plate (12) is slowly rotated in one direction or the other, depending upon the gearing (2). Thus the differential movement of the crank (13) relative to the plate (12) is obtained. The total movement of the crank is equal to its movement relative to the plate plus the movement

of the plate. The movement of the index plate (12) may be added or subtracted according to the direction of rotation of the plate.

Differential indexing heads are generally furnished with change gears as follows: 24, 24, 28, 32, 40, 44, 48, 56, 64, 72, 86, 100. With these change gears and three sets of standard index plates (B & S), it is possible to index any number from 1 to 382. Special gears having 46, 47, 52, 52, 58, 68, 70, 70 76 and 84 teeth may also be furnished for numbers from 383 to 1008 divisions. The differential method of indexing is employed when the problem cannot be worked by plain indexing.

<u>Rule for differential indexing</u>: The following are the different rules for determining gear ratio, indexing movement of the crank and the number of idlers required.

1. Gear ratio = $(A-N)\times 40/A$

   where, A = the selected number which can be indexed by plain indexing and the number is approximately equal to N.

   N = the required number of divisions to be indexed.

2. In the gearing ratio so calculated, the numerators of fraction indicate the driving gears on the index head spindle and the denominators indicate the driven gears on the index plate.

3. Index crank movement = $40/A$

   where, A is the selected number.

   The index crank will have to be moved by an amount given in the last formula for N number of times for complete division of the work.

   $1/N = 1/A + 1/N \times R/40$

   $1/N-1/A = R/(N\times 40)$ $(A-N)/(N\times A) = R/(N\times 40)$ $R=40\times(A-N)/A$

4. The index crank and the index plate should move in the same direction or opposite to each other depending on the type of gearing ratio and the selected number A chosen.

   If (A-N) is positive, the index plate must rotate in the same direction as the crank and if (A-N) is negative, the index plate must rotate in direction opposite to that of the crank.

To achieve these conditions, the number of idle gears used depends upon the following factors:

1. If the gear train is simple and (A — N) is positive, only one idle gear is used.
2. If the gear train is compound and (A — N) is positive, no idle gear is used.
3. If the gear train is simple and (A — N) is negative, two idle gears are used.
4. If the gear train is compound and (A — N) is negative, only one idle gear is used.

<u>Example 4:</u> Index 83 divisions.

First of all, find out whether the number can be indexed by plain indexing or not.

Index crank movement in plain indexing = 40/N = 40/83. Since, there is no 83 hole circle, the number cannot be indexed by plain indexing. Therefore, it is a case of differential indexing.

Using the last formula, assume A = 86, a number almost equal to 83 and can be indexed by plain indexing.

1. Gear ratio = (A-N)×40/A = (86-83) ×40/86 = 3×40/86 = 72/24×40/86
2. Therefore, Drivers = 72, 40 and Driven = 24, 86
3. Index crank movement = 40/86 = 20/43

For complete indexing, the index crank will have to be moved by 20 holes in 43 hole circle for 83 times.

4. As (A N) is positive and the gearing ratio is compound, no idle gear is required.

Angular indexing: The angular indexing is the process of dividing the periphery of a work in angular measurements and not by the number of divisions. The indexing method is similar to the plain indexing. There are 360 degrees in a circle, and when the index crank is rotated by 40 numbers of revolutions, the spindle rotates through one complete revolution or by 360 degrees. Therefore, one complete turn of the crank will cause the spindle and the work to rotate through 9 degrees. Thus in order to turn a work through a desired angle, the number of turns of the index crank required can be determined by dividing the angular displacement of the work expressed in degrees by the number 9. If the angular displacement is expressed in minutes then the turns of the index crank may be calculated by dividing the angle by 540. If the angle is expressed in seconds then it should be divided by a number 32400. If the result is a whole number, the index crank should be rotated through the full number of the calculated turns. If the result is a whole number and a traction, the part of the revolution of the crank is determined by using the index plate hole circles in the

similar manner as described under plain indexing. If the fractional division cannot be solved by plain indexing, an angular indexing chart should be consulted to obtain the index crank movement.

Rule for angular indexing: To find the index crank movement, divide the angle by 9 if it is expressed in degrees, by 540 if it expressed in minutes, and by 32400 if it is expressed in seconds.

Example 5: Index an angle 19° 40'

19° 40' = (19×60)+40 = 1180'

Index crank movement = 1180/540 = 2 5/27

The index crank should be moved two complete turns and 5 holes of 27 hole circle.

Spur Gear Milling Operation

The actual cutting of spur gear is done after determining the gear tooth properties, selecting the type -of indexing to be performed, and finding the correct number of form cutter from the aforementioned table. The speed and feed of the machine is next set. The speed should be slightly lower than the plain milling operation and the feed should be normal. The dividing head and the tailstock are next bolted on the table after setting their axis exactly perpendicular to the machine spindle. The cutter is next mounted on the arbor and it is then centered accurately with the dividing head spindle axis by adjusting the position of the table. The alignment of the cutter with the work axis is checked by raising the table when the centre line of the cutter must touch the centre point of the tailstock. This assures the radial setting of the cutter relative to the gear blank. The gear blank is next mounted between the two centres by a mandrel and is connected with the dividing head spindle. The proper index plate is next bolted on the dividing head and the positions of the crank pin and the sector arms are adjusted. For a smaller size of gear blank, the depth of cut is given equal to the full depth of the gear tooth. For this purpose, the table is raised till the cutter just touches the periphery of the gear blank. The micrometer dial of the vertical feed screw is set to zero in this position. The table is next raised to give the required depth of cut by turning the dial through the calculated number of divisions. The machine is started and the feed is applied to finish the first tooth space of the gear. After the end of the cut, the table is brought back to the starting position and then the blank is indexed for the next tooth space. The operation is repeated till all the gear teeth are cut.

Example 6: Calculate all machining particulars for cutting a spur gear of 3 module and 54 teeth with

proper index plate hole circle and sector.

1. Determination of gear tooth proportions:
    a. Pitch circle diameter = Z_m = 3×54 = 162 mm.
    b. Addendum = m = 3 mm.
    c. Outside diameter = m(z+2) = 168 mm
    d. Dedendum = 1.25×m = 3.75 mm
    e. Tooth depth = h = 2.25×m = 6.75 mm
    f. Tooth thickness = s = 1.5708×m = 4.7124 mm
2. Indexing: Index crank movement = 40/N = 40/54 = 20/27, the index crank will be moved by 20 holes in 27 hole circle for 54 times.
3. Selection of cutter: Using the gear cutter selection table, the gear cutter No. 3 is chosen.
4. Selection of cutting speed, feed and depth of cut: The speed and feed of the machine is determined after considering various machining conditions. The depth of cut is set to 6.75 mm, which is the tooth depth of the gear.

Fundamentals of Helical Gear Milling by a Form Disc cutter

The helical gears are cut in a universal milling machine by helical milling operation. The principle of helical milling can be explained as the process of producing helical grooves on the periphery of the work. This is done by mounting the work at the and of the dividing head spindle and then connecting the worm spindle with the table feed screw through a train of gearing, so that when the table with the work is fed longitudinally past the cutter, the work also rotates through a calculated amount to produce a helical groove of a given lead. The rotary speed of the work and the feed of the table determine the amount of lead of the helix being cut. The helical milling operation is performed for producing helical milling cutters, cutting flutes on drills or reamers and for milling helical gears. The following procedure must be adapted to mill helical gears.

1. Determination of the gear tooth proportions.
2. Making arrangement for indexing.
3. Selection of table gear train.
4. Selection of cutter and setting of the table.
5. Determination of speed, feed, and depth of cut.

Gear tooth proportions:

The definitions of spur gear elements described earlier hold good for helical gear. The definitions of certain additional elements related to the helical gears are given below:

Helix: On a cylinder of revolution this is a curve whose tangents are inclined at a constant angle to the axis of the cylinder. Figure 9 shows a helix

Lead: The distance between two consecutive intersections of a helix by a straight generator of the cylinder on which it lies . Figure 9 shows the lead of a helix.

Helix angle: The acute angle between the tangent to a helix and the straight generator of the cylinder on which it lies. The formula for the helix angle is given below

$\tan \beta = \pi D/L$

where, β = helix angle

D = the pitch diameter of the work

L = the lead of the helix

Normal circular pitch: The length of the arc between similar faces of adjacent teeth measured on the pitch cylinder in a plane perpendicular to the teeth.

The normal circular pitch $= CP_n = CP \cos \beta = \pi \times \cos \beta / DP$

All gear calculations are based upon normal pitch and not upon the circular pitch measured in the plane of rotation. Normal pitch of a helical gear changes with the helix angle.

Normal diametral pitch:

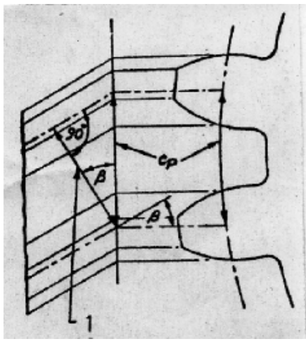
It is the quotient of the number of teeth by the diametral pitch. The normal diamteral pitch $= DP_n = \pi/CP_n = DP/\cos \beta = N/(PD \cos \beta)$

Normal module

The quotient of the normal pitch by the number of teeth.

The formula for normal module is:

Normal module $= m_n = CP_n/\pi = \cos \beta \,/\, DP = m \cos \beta$.



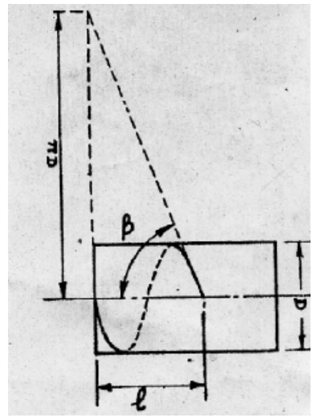


Fig. 9: Nomenclature for helical gears.

Methods of indexing:

In helical milling, only direct and simple methods of indexing are performed to divide the periphery of a work. The differential method of indexing cannot be employed in connection with the helical milling, because with this system ofindexing the worm shaft of the index head must be geared to the spindle, but as the worm shaft is already geared with the table feed screw, there is no provision for duplicate connection. So the differential method of indexing cannot be used.

Change gear calculations:

During helical milling, the workpiece must rotate through one complete revolution by the time the table moves through a distance equal to the lead of the helix. This is done by a selected train of gearing connected between the table lead screw and the dividing head worm shaft.

The gearing arrangement for helical milling is shown in Figure 10. A train of gearing is connected between the lead screw (2) and the shaft (11). The gear on the lead screw (2) is the driver and the gear on the shaft (11) is tae driven gear. When the lead screw (2) of the table is rotated within the nut (3), the motion is transmitted through the change gears (1) to the two miter gears (10) mounted on the shaft (11) and on the sleeve. The index plate (9) is screwed on the other end of the sleeve, and the crank pin is kept engaged into any one of the holes on the index plate. While helical milling, the lock pin at the back of the plate is removed. Motion is thus communicated from the miter gears (10) to the worm shaft through the index plate (9) as the index plate and the crank becomes one unit, causing the worm (7) and the worm gear (8) to rotate. As the worm gear (8) has 40 teeth and the worm (7) is single threaded, (40) turns of the worm (7) or the

driven shaft (11) are required to turn the worm gear (8) and the work through one complete revolution. The change gears (1) between the lead screw (2) and the shaft (11) can be so arranged that when the shaft (11) will rotate through 40 number of revolutions, the lead screw (2) will rotate by that number of revolutions which will cause the lead screw (2) to move axially within the nut (3) equal to the lead of the helix being cut. Thus when the table holding the work is fed a distance equal to the lead of the helix being cut, the work is rotated by one complete revolution. This is the guiding principle for determining the formula for change gears. The formula is derived below.

Let T_1 = pitch of the lead screw in mm.

T_2 = Lead of the helix to be milled in mm.

Then the number of turns of lead screw required to move the table through T_2 mm. (The lead of the helix) = T_2 / T_1.

By the time the table moves T_2 mm, the work should turn by l revolution.

No. of turns of work / No of turns of lead screw = T_1 / T_2

By the time the work turns by 1 revolution, the worm shaft or the driven shaft (11) turns by 40 revolutions.

No. of turns of driven shaft / No. of turns of lead screw = $40 \times T_1 / T_2$

The number $40 \times T_1$ is called the lead of the machine.

In British or American manufactured milling machines, the pitch of the lead screw or T_1 is equal to 1/4 inch.

Lead of the machine in British unit = $40 \times T_1 = 10$ inch.

The usual value of the lead screw pitch in metric unit is 6mm.

Lead of the machine in metric unit = $40 \times 6 = 240$ mm.

Gear on the lead screw is the driver gear and the gear on the worm shaft is the driven gear.

The change gears employed for differential indexing can be used for helical milling also.

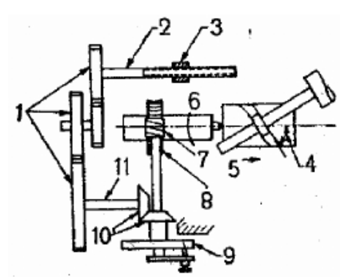


Fig. 10 Gearing arrangement for helical milling

1. *Change gears*, 2. *Table leadscrew*, 3. *Nut*, 4. *Helix angle*, 5. *Direction of table feed*, 6. *Direction of spindle rotation*, 7. *Worm*, 8. *Worm gear*, 9. *Index plate*, 10. *Mitre gears*, 11. *Driven shaft*.

Selection of helical milling cutter:

The tooth profile of a helical milling cutter should correspond to the tooth form across the-normal. As the tooth form of a helical gear across the normal changes with the helix angle, a cutter which is used to produce a spur gear of same number of teeth as the helical gear will not serve the purpose. The modified formula for selecting the helical milling cutter is:

$$Z' = \frac{Z}{\cos^3 \beta}$$

where Z' = the number of teeth for which the cutter is selected.

Z = the number of teeth in the helical gear.

β = helix angle.

Table setting:

While helical milling, the table of the universal milling machine must be swiveled to the required helix angle of the work. This is necessary to produce the groove or the tooth space conforming to the cutter tooth profile. Figure 11 shows the effect of Swiveling and not swiveling the table to the required helix angle. It is seen that when the table is swiveled, a groove of correct width and proper contour as that of the cutter is produced. The helix angle of the work is calculated from the last formula.

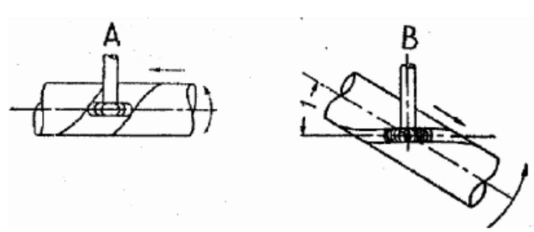


Fig. 11: with and without swiveling the table.

Helical gear milling operation:

The helical gear milling operation is taken in hand after preparing the gear blank to the required size and calculating the necessary tooth dimensions. The work is next mounted on a mandrel and supported between the centers of the dividing head and the tailstock. The spindle of the dividing head and the tailstock are aligned so that they may be perpendicular to the machine spindle. The proper cutter is chosen after

necessary calculations and it is mounted on the arbor. The cutter is next centered directly above the axis of the work in this position of the table following the procedure described under spur gear milling operation. The required helix angle is calculated and the table is swiveled to the correct position. The proper index plate is mounted on the dividing head and the crank pin is pushed into the hole of the required hole circle. The sector arm is set for the correct number of spaces and the lock pin for the index plate is removed. The cutter is next made to touch the peripheral surface of the work and the required depth of cut is given. The speed and feed of the machine will be similar as that of spur gear milling. The actual milling of helical tooth spaces is practically the same is if they are parallel to the axis, due to the angular setting of the work. The machine is next started and the first tooth space is milled in one or two cuts. At the end of each out, the table is brought back to the starting position. After the first tooth space is finished, the index pin is withdrawn from the index plate, which causes the worm shaft to be disengaged with the table feed tearing. Indexing is performed in the usual way and the crank pin is snapped in position. The second cut is taken, and the operation is repeated until all the teeth on the gear are finished.

Example 7: Calculate all machining particulars for milling a helical gear having 48 teeth, helix angle of 45 degrees and a module of 6 mm.

1. Gear tooth proportions:
   a. Pitch diameter = $Z_m = 48 \times 6 = 288$ mm.
   b. Normal module $m_n = m \cos \beta = 6 \cos 45° = 4.2426$ mm.
   c. Outside diameter or blank diameter $Z_m+2m_n=288+2 \times 4.2426 = 296.485$ mm.
   d. Tooth depth = $2.25 \times m_n = 2.25 \times 4.2426 = 9.548$ mm.
2. Indexing:
   a. Index crank movement = 40 / N = 40 / 48 = 15 /18
   b. The index crank will be moved by 15 holes in 18 hole circle for 48 times.
3. Selection of table gear train:
   a. Assuming pitch of the lead screw of the machine equal to 6 mm. The lead of the machine = $40 \times T_1 = 240$ mm.
   b. The lead of the helix is calculated from: $\tan \beta = \pi D / L \rightarrow L = 905.8$ mm.
   c. The value of lead L is corrected and taken as 900 mm to suit to the available gear train. This will alter tote helix angle very slightly.
   d. The change gears are calculated from:.

i. Lead of the machine / Lead of the work = $40 \times T_1 / T_2$ = 240/900 = 32/40 × 24/72

ii. The gears 32, 24 are the driver gears and 40, 72 are the driven gears.

4. Selection of cutter:
   a. Using the last formula $Z' = 48 / \cos^3 \beta$ = 135.5 or 136.
   b. The selection of cutter is based on 136 teeth. Therefore, No. 1 gear cutter will be used.
5. Setting the table:
   a. The table must be swiveled to the helix angle of 45°.

Gear Cutting by a Formed End Mill:

The end mills having cutting edges formed to correspond to the tooth space of a gear are employed to cut a spur, helical or a herringbone gear in a milling machine. The end mills are used to cut gears of large module from 20 mm and larger where ordinary disc type cutters are unsuitable to excessive cutting pressure required. The cutting process described under disc cutter, also holds for an end mill.

Gear Cutting By a formed Single Point Tool:

A single point cutting tool having cutting edges formed to correspond to the tooth space of a gear is employed to cut a spur or a bevel gear in a shaping or a planing machine. The work is mounted between the two centres and the tool or the work is reciprocated to produce the required profile of the tooth space.

Broaching Gear Teeth

A broaching tool having formed cutting edges is employed for producing internal gears of accurate shapes in a broaching machine. Very small internal gears are cut in one operation by a broaching tool having a number of cutting edges equal to the number of teeth on the gear. When large gears are to be machined, the rotary table holding the gear blank is indexed by one tooth after each stroke of the broach. At the end of each cutting stroke, the work is shifted slightly off the centre to provide relief to the cutting edges during the return stroke of the broach.

Generation Method (Shaping)

Most high-quality gears that are made by machining are made by the generating process. This process is based on the principle that any two involute gears, or any gear and a rack, of the same diametral pitch will mesh together properly. Utilizing this principle, one of the gears (or the rack) is made into a cutter by proper sharpening. It can be used to cut into a mating gear blank and thus generate teeth on the blank. The two principal methods for gear generating are shaping and hobbing.

To carry out the shaping process, the cutter and the gear blank must be attached rigidly to their respective shafts, and the two shafts must be interconnected by suitable gearing so that the cutter and the blank rotate positively with respect to each other and have the same pitch-line velocities. To start cutting the gear, the cutter is reciprocated and is fed radially into the blank between successive strokes. When the desired tooth depth has been obtained, the cutter and blank are then slightly indexed after each cutting stroke. The resulting generating action is indicated schematically in the upper diagram of Figure 12a and shown in the cutting of an actual gear tooth in Figure 12b.

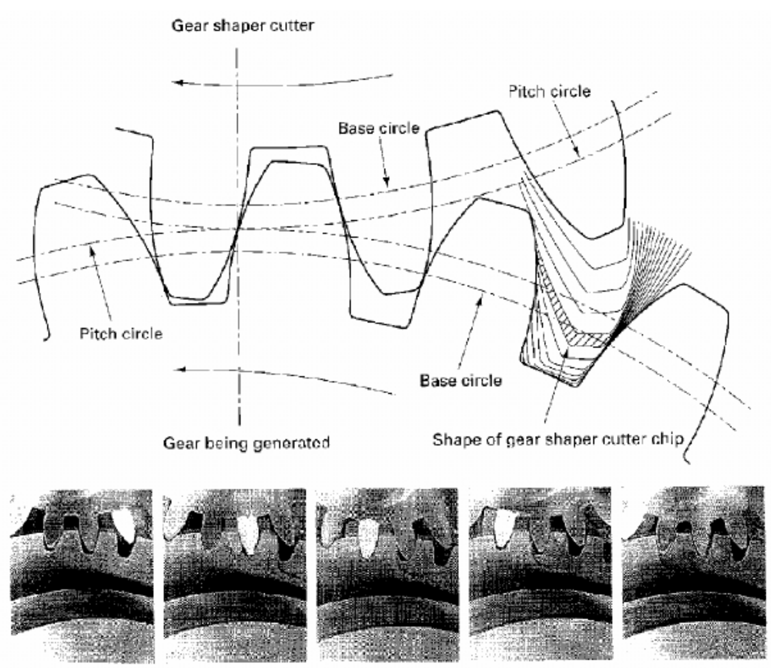


Fig. 12a, 12b: (top) generation action of a gear shaper cutter; (bottom) series of photographs showing various stages in generating one tooth in a gear by means of gear shaper action.

Figure 13 shows a machine called a gear shaper. Gear shapers generate gears by a reciprocating tool motion. The gear blank is mounted on the rotating table (or vertical spindle) and the cutter on the end of a vertical, reciprocating spindle. The spindle and the table are connected by means of gears so that the cutter and gear blank revolve with the same pitch-line velocity. Cutting occurs on the downstroke (sometimes on the upstroke). At the end of each cutting stroke, the spindle carrying the blank retracts slightly to provide clearance between work and tool on the return stroke. Because of the reciprocating action of the cutter, these machines are commonly called gear shapers. Details of the cutter are shown in Figure 14.

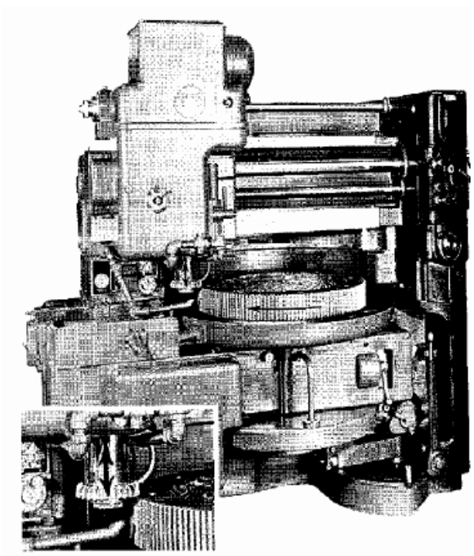


Fig. 13: Gear shaper machine

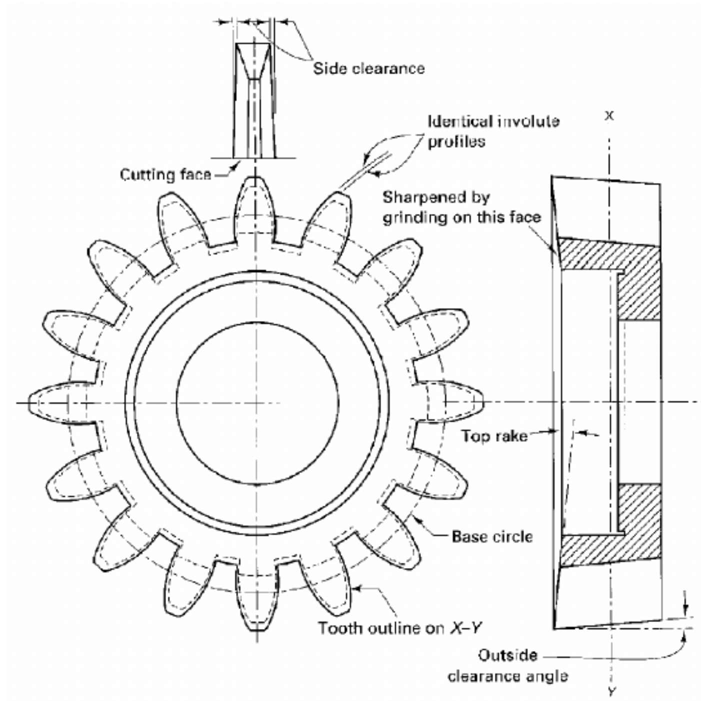


Fig. 14: Details of the cutter used in gear shaper machine.

The conventional cutter for gear shaping is made from high speed steel which can be coated to improve wear life with a layer of titanium nitride (TiN) using the physical vapor deposition (PVD) process. Recently, new throwaway disk-shape insert tools have been developed for gear shaping, eliminating regrinding and recoating operations on the conventional tools. Regrinding the conventional cutter required two adjustments (resetting operations) on the machine tool. Because the throwaway blades are all sized the same, machine resetting after cutting tool changeover is eliminated.

To start cutting a gear, the cutter is fed radially inward before each cutting stroke, as it

and the blank rotate. When the proper depth is reached, the inward feed stops and the cutter and blank continue their rotation until all the teeth have been machined by the generation process.

Either straight- or helical-tooth gears can be cut on gear shapers. To cut helical teeth, both the cutter and the blank are given an oscillating rotational motion during each stroke of the cutter, turning in one direction during the cutting stroke and in the opposite direction during the return stroke. Because the cutting stroke can be adjusted to end at any desired point, gear shapers are particularly useful for cutting cluster gears. Some machines can be equipped with two cutters simultaneously to cut two gears, often of different diameters. Gear shapers also can be adapted for cutting internal gears.

Special types of gear shapers have been developed for mass-production purposes. The rotary gear shaper essentially is 10 shaper units mounted on a rotating base and having a single drive mechanism. Nine gears are cut simultaneously while a finished gear is removed and a new blank is put in place on the tenth unit. Planetary gear shapers holding six gear blanks move in planetary motion about a large, central gear cutter. The cutter has no teeth in one portion to provide a space where the gear can be removed and a new blank placed on the empty spindle.

CNC gear shapers are now available with hydro-mechanical stroking systems which produce a uniform cutting velocity during the cutting portion of the downstroke. These machines can operate at 500 to 1700 rpm and use TiN-coated cutters to enhance tool life.

Generation Method (Hobbing)

Involute gear teeth could be generated by a cutter that has the form of a rack. Such a cutter would be simple to make but has two major disadvantages. First, the cutter (or the blank) would have to reciprocate, with cutting occurring only during one stroke direction. Second, because the rack would have to move longitudinally as the blank rotated, the rack would need to be very long (or the gear very small) or the two would not be in mesh after a few teeth were cut. A hob overcomes the preceding two difficulties. As shown in Figure 15, a hob can be thought of, basically, as one long rack tooth that has been wrapped around a cylinder in the form of a helix and fluted at intervals to provide a number of cutting edges. Relief is provided behind each of the teeth. The cross section of each tooth, normal to the helix, is the

same as that of a rack tooth. (A hob can also be thought of as a gashed worm gear.)

The action of a hobbing machine cutting a spur gear is illustrated in Figure 16. To cut a spur gear, the axis of the hob must be set off from the normal to the rotational axis of the blank by the helix angle of the hob. In cutting helical gears, the hob must be set over an additional amount equal to the helix angle of the gear. The cutting of a gear by means of a hob is a continuous action. The hob and the blank are connected by proper gearing so that they rotate in mesh. To start cutting a gear, the rotating hob is fed inward until the proper setting for tooth depth is obtained. The hob is then fed in a direction parallel with the axis of rotation of the blank. As the gear blank rotates, the teeth are generated and the feed of the hob across the face of the blank extends the teeth to the desired tooth face width.

Hobbing is rapid and economical. More gears are cut by this process than by any other. The process produces excellent gears and can also be used for splines and sprockets. Single-, double-, and triple-thread hobs are used. Multiple-thread types increase the production rate but do not produce accuracy as high as single-thread hobs.

Gear-hobbing machines are made in a wide range of sizes. Machines for cutting accurate large gears frequently are housed in temperature-controlled rooms, and the temperature of the cutting fluid is controlled to avoid dimensional change due to variations in temperature.

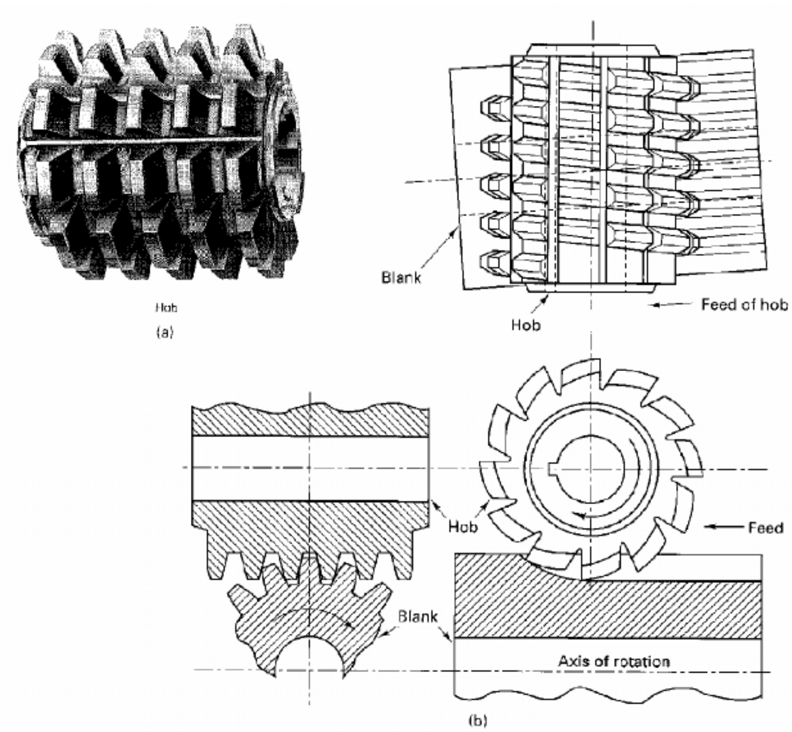


Fig. 15: Hob and the relationship of the hob to the gear blank in machining a spur gear by hobbing

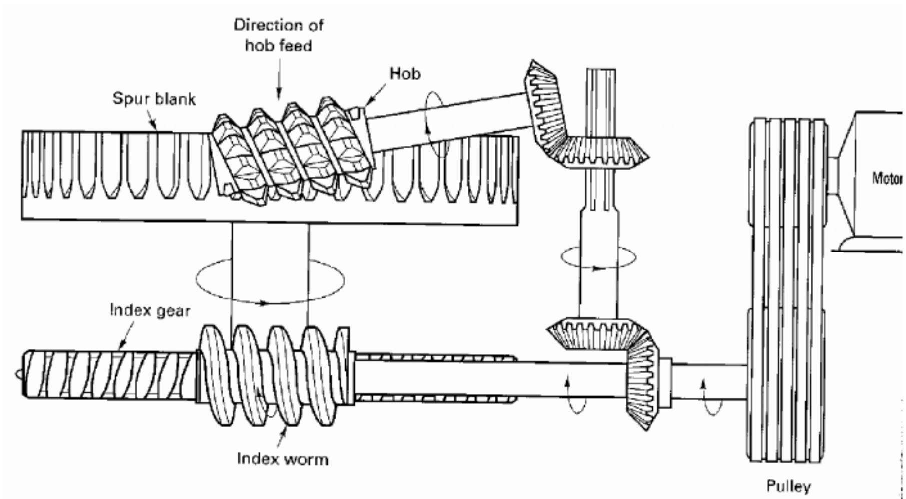


Fig. 16: Schematic for a gear hobbing machine for hobbing a spur gear

Cold-Roll Forming

The manufacture of gears by cold-roll forming has been highly developed and widely adopted in recent years. Currently, millions of high-quality gears are produced annually by this process; many of the gears in automobile transmissions are made this way. As indicated in Figure 17, the process is basically the same as that by which screw threads are roll formed, except that in most cases the teeth cannot be formed in a single rotation of the forming rolls; the rolls are fed inward gradually during several revolutions.

Because of the metal flow that occurs, the top lands of roll-formed teeth are not smooth and perfect in shape; a depressed line between two slight protrusions can often be seen, as shown encircled in Figure 18. However, because the top land plays no part in gear-tooth action, if there is sufficient clearance in the mating gear, this causes no difficulty. Where desired, a light turning cut is used to provide a smooth top land and correct addendum diameter.

The hardened forming rolls are very accurately made, and the roll-formed gear teeth usually have excellent accuracy. In addition, because the severe cold working produces tooth faces that are much smoother and harder than those on ordinary machined gears, they seldom require hardening or further finishing, and they have excellent wear

characteristics.

The process is rapid (up to 50 times faster than gear machining) and easily mechanized. No chips are made and thus less material is needed. Less skilled labor is required. Small gears often are made by rolling a length of shaft and then slicing off the individual gear blanks.

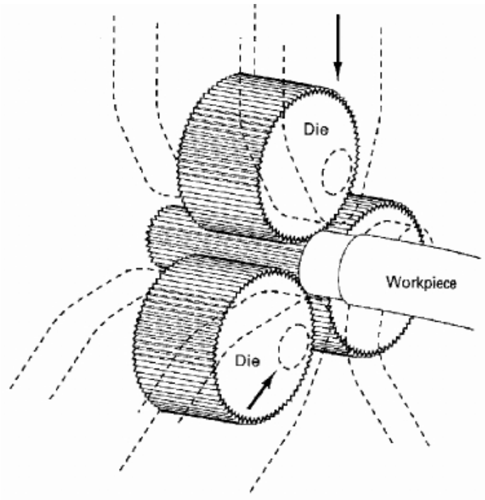


Fig. 17: Method of forming gear teeth by cold forming

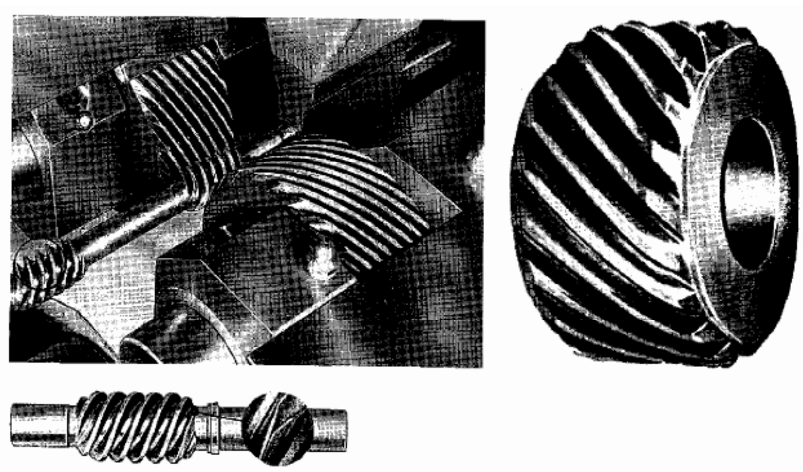


Fig. 18: Worm gear being rolled by means of rotating rolling tools

Other Gear Making Processes

Gears can be made by the various casting processes. Sand-cast gears have rough surfaces and are not accurate dimensionally. They are used only for services where the gear moves slowly and where noise and inaccuracy of motion can be tolerated. Gears made by die casting are fairly accurate and have fair surface finish. They can be used to transmit light loads at moderate speeds. Gears made by investment casting may be accurate and have good surface characteristics. They can be made of strong materials to permit their use in transmitting heavy loads. In many instances, gears that are to be finished by machining are made from cast blanks, and in some larger gears the teeth can be cast to approximate shape to reduce the amount of machining.

Large quantities of gears are produced by blanking in a punch press. The thickness of such gears usually does not exceed about 1.5 mm. By shaving the gears after they are blanked,

excellent accuracy can be achieved. Such gears are used in clocks, watches, meters, and calculating machines. Fine blanking is also used to produce thin, flat gears of good quality.

High-quality gears, both as to dimensional accuracy and surface quality, can be made by the powder metallurgy process. Usually, this process is employed only for small sizes, ordinarily less than 25 mm in diameter. However, larger and excellent gears are made by forging powder metallurgy pre-forms. This result in a product of much greater density and strength than usually can be obtained by ordinary powder metallurgy methods and the resulting gears give excellent service at reduced cost. Gears made by this process often require little or no finishing.

Large quantities of plastic gears are made by plastic molding. The quality of such gears is only fair, and they are suitable only for light loads. Accurate gears suitable for heavy loads frequently are machined out of laminated plastic materials. When such gears are mated with metal gears, they have the quality of reducing noise.

Quite accurate small gears can be made by the extrusion process. Typically, long lengths of rod, having the cross section of the desired gear, are extruded. The individual gears are then sliced from this rod. Materials suitable for this process are brass, bronze, aluminum alloys, magnesium alloys, and occasionally, steel.

Gear Finishing

To operate efficiently and have satisfactory life, gears must have accurate tooth profiles and the faces of the teeth must be smooth and hard. These qualities are particularly important when gear must operate quietly at high speeds. When they are produced rapidly and economically by most processes except cold-roll forming, the tooth profiles may not be as accurate as desired, and the surfaces are somewhat rough and subject to rapid wear. Also, it is difficult to cut gear teeth in a hardened gear blank, and therefore, economy dictates that the gear is to be cut in a relatively soft blank and subsequently be heat treated to obtain greater hardness. Such heat treatment usually results in some slight distortion and surface roughness. Although most roll-formed gears have sufficiently accurate profiles, and the tooth faces are adequately smooth and frequently have sufficient hardness, this process is feasible only for relatively small gears. Consequently, a large proportion of high-quality gears are given some type of finishing operation after they have received primary machining or after heat treatment. Most of these finishing operations can be

done quite economically because only minimal amounts of metal are removed.

Gear shaving is the most commonly used method for finishing spur and helical gear teeth prior to hardening. The gear is run, at high speed, in contact with a shaving tool, usually of the type shown in Figure 19. Such a tool is a very accurate, hardened, and ground gear that contains a number of peripheral serrations, thus forming a series of sharp cutting edges on each tooth. The gear and shaving cutter are run in mesh (Figure 20). As they rotate, the gear is reciprocated longitudinally across the shaving tool (or vice versa). During this action, which usually requires less than 1 minute, very fine chips are shaved from the gear-tooth faces, thus eliminating any high spots and producing a very accurate tooth profile.

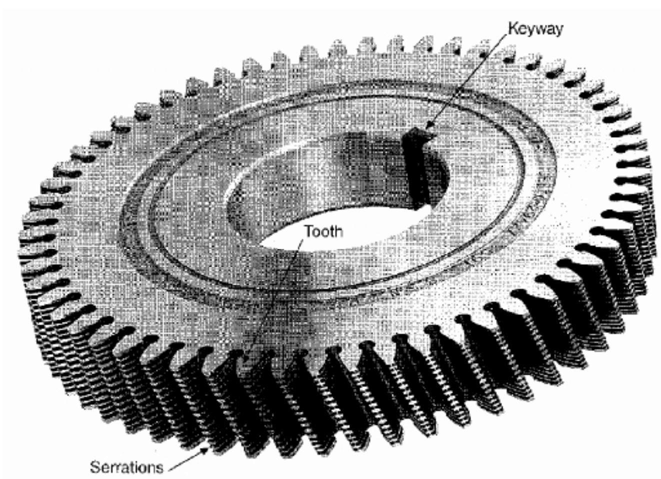


Fig. 19: Rotary gear shaving cutter

Rack shaving cutters sometimes are used for shaving small gears, the cutter reciprocating lengthwise, causing the gear to roll along it, as it is moved sideways across the cutter and fed inward.

Although shaving cutters are costly, they have a relatively long life because only a very small amount of metal is removed, usually 0.025 to 0.1 mm. Some gear-shaving machines produce a slight crown on the gear teeth during shaving. Most gears are not hardened prior to shaving, although it is possible to remove very small amounts of metal from hardened gears if they are not too hard. However, modern heat-treating equipment makes it possible to harden gears after shaving without harmful effects, and therefore this practice is usually

followed.

Roll finishing is a cold-forming process that is used to finish helical gears. The unhardened gear is rolled with two hardened, accurately formed rolling dies. The center distance between the dies is reduced to cold work the surfaces and produce highly accurate tooth forms. High points on the unhardened gear are plastically deformed so that a smoother surface and more accurate tooth form are achieved. Because the operation is one of localized cold working, some undesirable effects may accrue, such as localized residual stresses and non-uniform surface characteristics.

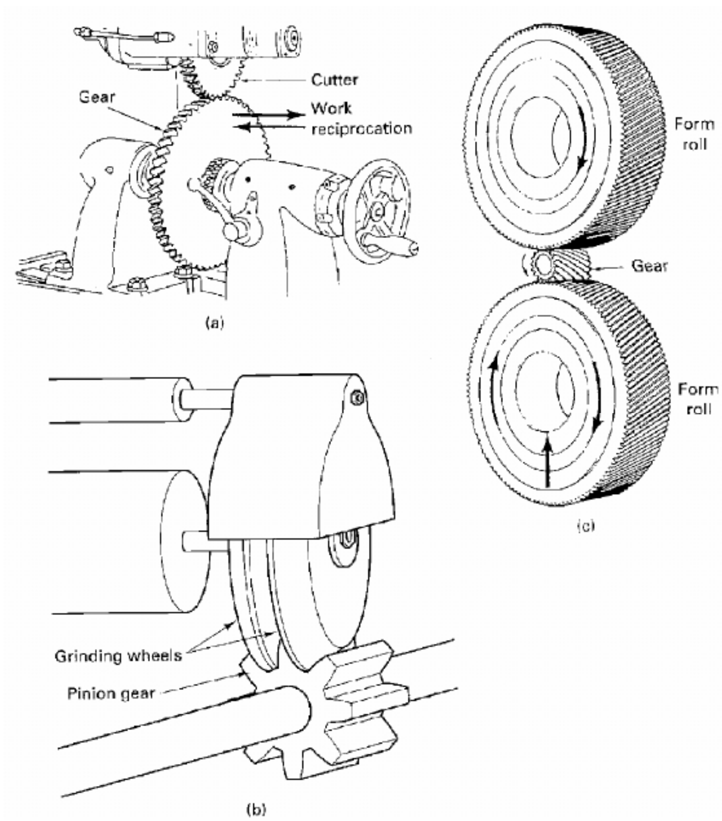


Fig. 20: Methods for gear finishing by shaving, grinding, and roll forming or finishing

Grinding is used to obtain very accurate teeth on hardened gears. Two methods are used. One employs a formed grinding wheel that is trued to the exact form of a tooth by means of diamonds mounted on a special holder and guided by a large template. The

other method is involute-generation grinding, which uses straight-sided grinding wheels which simulate one side of a rack tooth. The surface of the gear tooth is ground as the gear rolls (and reciprocates) past the grinding wheels. Grinding produces very accurate gears, but because it is slow and expensive, it is used only on the highest-quality, hardened gears.

Lapping can also be used for finishing hardened gears. The gear to be finished is run in contact with one or more cast-iron lapping gears under a flow of very fine abrasive in oil. Because lapping removes only a very small amount of metal, it usually is employed on gears that previously have been shaved and hardened. This combination of processes produces gears that are nearly equal to ground gears in quality but at considerably lower cost.

Gear Inspection

As with all manufactured products, gears must be checked to determine whether the resulting product meets the design specifications and requirements. Because of their irregular shape and the number of factors that must be measured, inspection of gears is somewhat difficult. Among the factors to be checked are linear tooth dimensions such as thickness, spacing, depth, and so on; tooth profile; surface roughness; and noise. Several special devices, most of them automatic or semiautomatic, are used for such inspection.

Gear-tooth vernier calipers can be used to measure the thickness of gear teeth on the pitch circle (Figure 21).

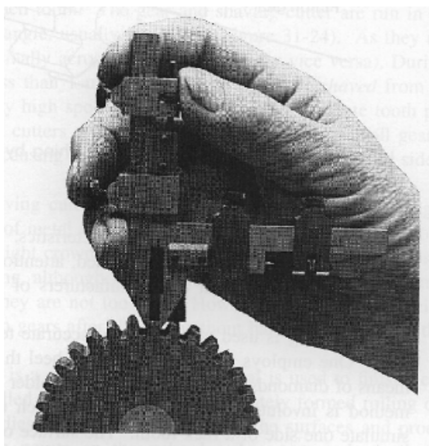


Fig. 21: Using gear-tooth caliper to check the tooth thickness at the pitch circle